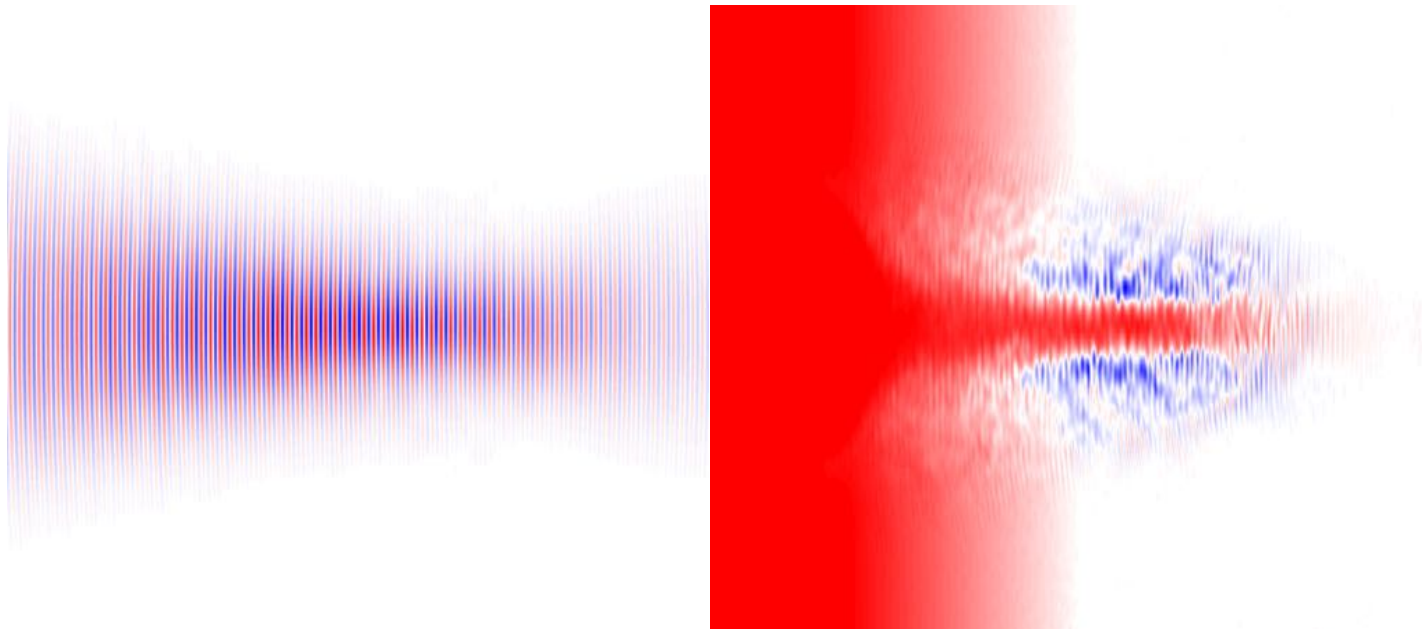


# Plasma Ion-Channel Undulator (PICU)

CO<sub>2</sub> laser-driven plasma structures  
undulating an externally injected e<sup>-</sup> beam



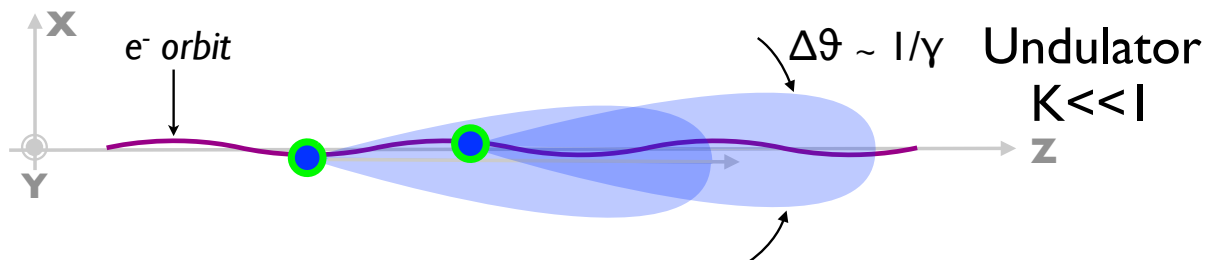
S. Rozario, **A. Sahai**, J. C. Wood, Z. Najmudin  
[a.sahai@imperial.ac.uk](mailto:a.sahai@imperial.ac.uk)

# Outline

- Background & Motivation
- Description of **Plasma Ion-Channel Undulator**
- **Laser-plasma** interaction challenges
- **PIC** simulation – laser-plasma expectations
- expt. setup / diagnostics & expected results
- Summary

# Background

## Radiation from insertion devices

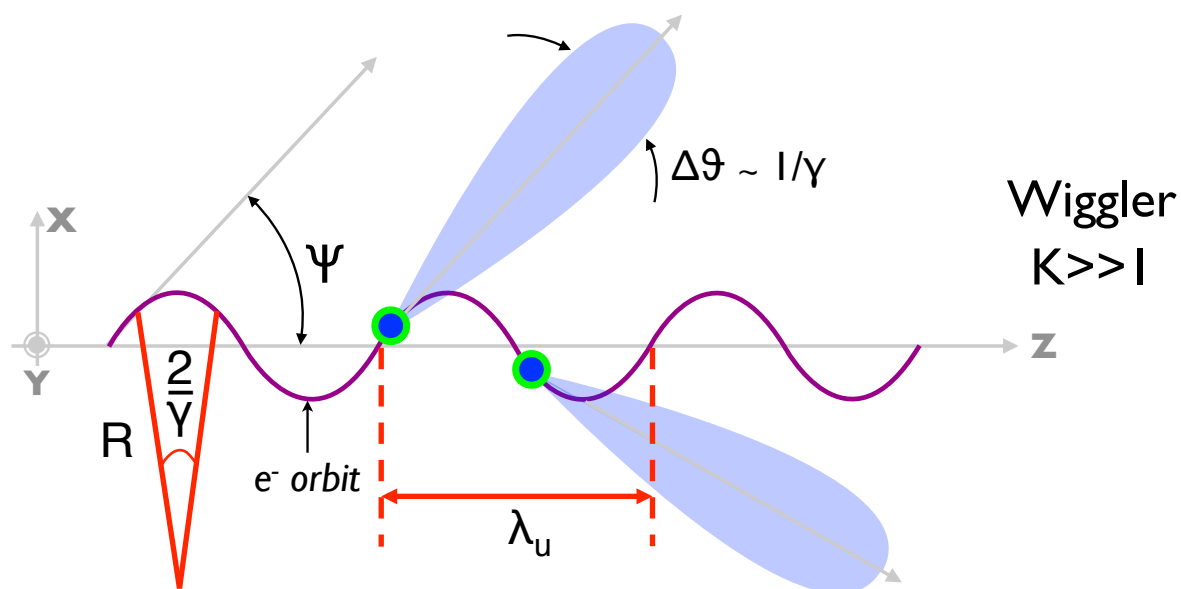


### Undulator

$$2R/\gamma \gg \lambda_u/2$$

$$K = \gamma\lambda_u/R, K \ll 1$$

degree of coherence



### Wiggler

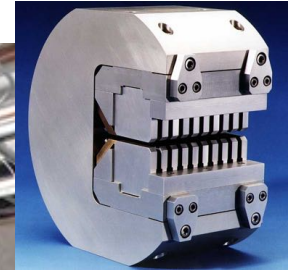
$$\psi \gg \Delta\theta$$

$$K \gg 1$$

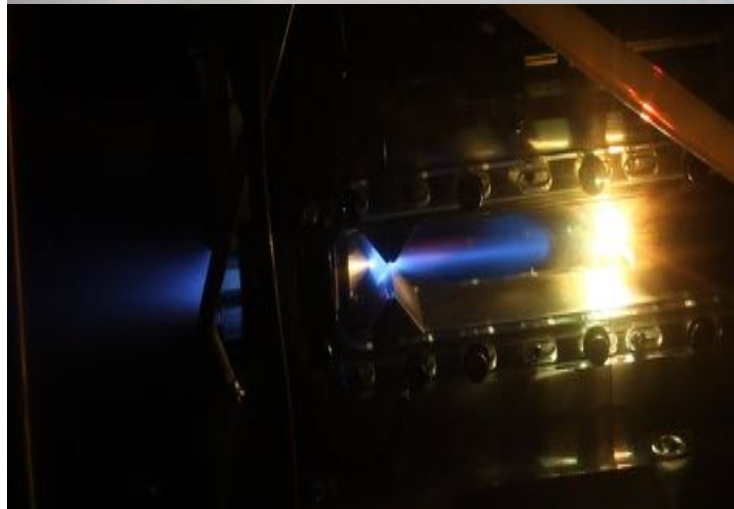
several harmonics

# Motivation

Conventional  
Undulators  
(several meters long)

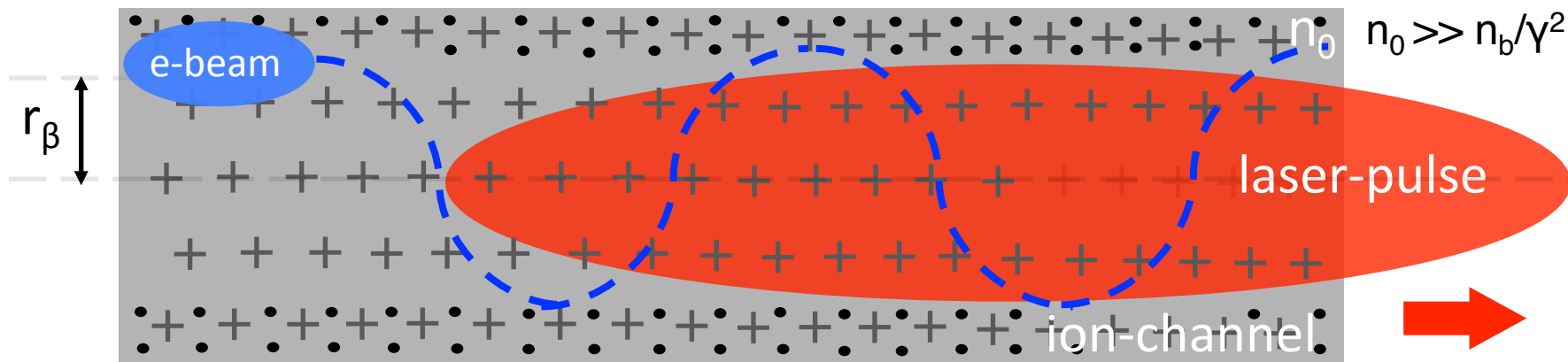


Plasma Ion-Channel  
Undulator  
(centimeter scale)



a few  
centimeters long  
gas-cell

## Description of the idea - I



**assumptions**  $v_{laser} = v_{structure} \simeq c$   $\tau_{laser} \gg \lambda_{pe}$   $\tau_{laser} \leq 2\pi/\omega_{pi}$

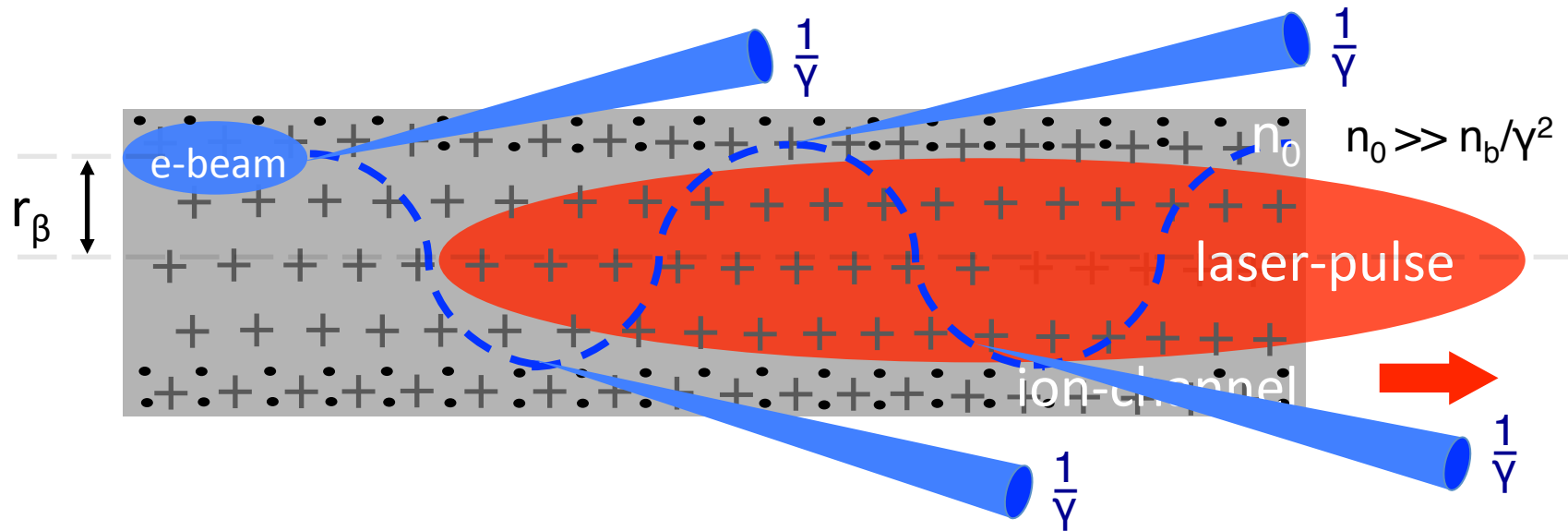
Plasma frequency :  $\omega_{pe} = \sqrt{4\pi e^2 n_0 / m_e}$

Betatron frequency :  $\omega_{\beta}(t) \simeq \omega_{pe} / \sqrt{2\gamma(t)}$

Undulator wavelength :  $\lambda_u(t) \equiv \lambda_{\beta}(t) = \sqrt{2\gamma(t)} \lambda_{pe}$

Strength parameter :  $K(t) = r_{\beta}(t) k_{pe} \sqrt{2\gamma(t)}$

## Description of the idea - II



Rad. Freq. ( $n_{th}$  harmonic) :  $\omega_{rad}[n] = 2\gamma^2\omega_\beta/(1 + K^2/2) [n]$

Ave. Power **per**  $e^-$  **per**  $\lambda_\beta$  :  $\bar{P}_\beta = r_e m_e c^3 \gamma^2 K^2 k_\beta^2 / 3$

Rad. Energy **per**  $e^-$  : 
$$W_\beta = \bar{P}_\beta \times N_\beta \times \lambda_\beta / c$$

$$= 2\pi/3 r_e m_e c^2 \gamma^2 K^2 k_\beta N_\beta$$

# Photons Rad. **per**  $e^-$  : 
$$\bar{N}_s = W_s / \hbar \omega_{rad}$$

$$= \pi/3 \alpha_{fine} (1 + K^2/2) K^2 N_\beta / [n]$$

## Laser-Plasma challenges

- Laser self-guiding in plasma [ $P/P_c$  &  $Z_R$ ]
- Ion-channel velocity [ $Y_\phi$ ] vs. beam velocity [ $Y_{\text{beam}}$ ]
- Extent of cavitation [ $\delta n/n$  vs.  $a_0$ ]
- Laser focal-spot matching in plasma [ $w_0$  vs.  $c/\omega_p a_0^{0.5}$ ]
- Betatron wavelength vs. laser guiding distance [ $\lambda_\beta / Z_R$ ]
- Beam radius vs. laser focal-spot [ $\sigma_r / w_0$ ]

# Laser-Plasma BNL-ATF parameters

Table 1: ATF (2017)  $e^-$  beam and  $CO_2$ -laser properties

$e^-$ beam	
Input energy (E)	80 MeV
Emittance	1 mm-mrad
$\sigma_r$	50 $\mu\text{m}$ r.m.s.
$\beta_{beam}$	2.5 mm
Charge	100 pC
Bunch length ( $\sigma_z/c$ )	1 psec
$\Delta E/E$	0.15 r.m.s.
$CO_2$ laser	
$\lambda_0$	10.3 $\mu\text{m}$
$w_0$ ( $1/e^2$ radius)	30 - 100 $\mu\text{m}$
$Z_R$	0.3 - 3 mm
Pulse energy	5 J
Pulse length	3.5 - 1.5 psec
Pulse power	1 - 3 TW
Polarization	Linear

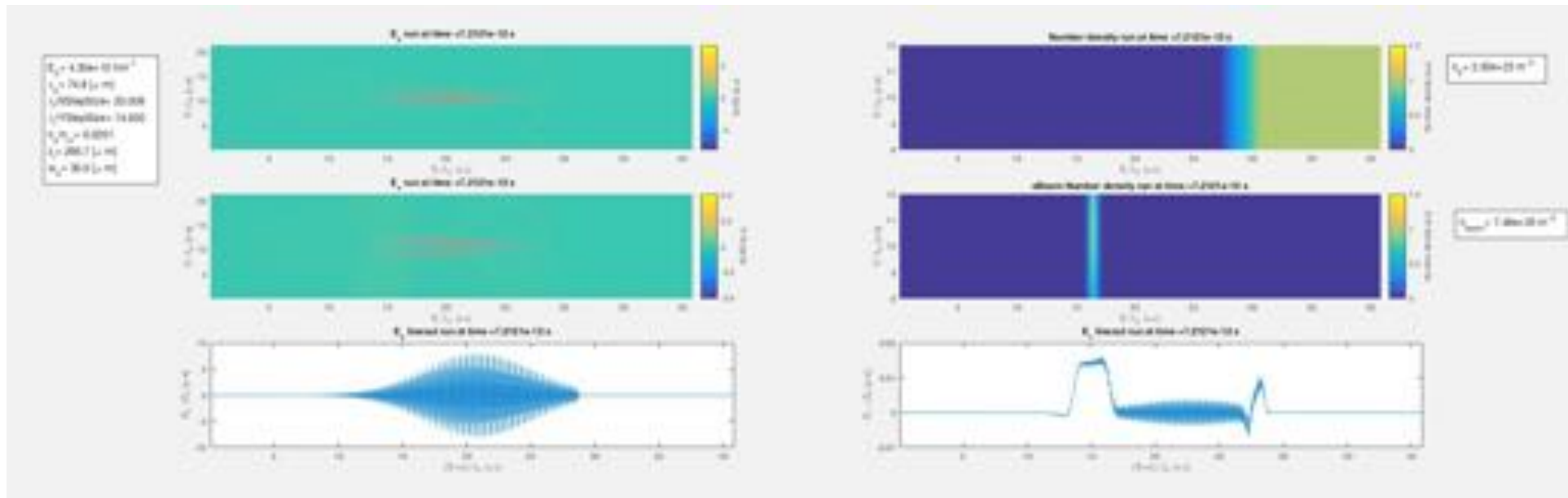
# Laser-Plasma BNL-ATF-II parameters

Table 2: ATF-2  $e^-$  beam and  $CO_2$ -laser properties

$e^-$ beam	
Input energy (E)	500 MeV
Emittance	
$\sigma_r$	
$\beta_{beam}$	
Charge	10-100 pC
Bunch length ( $\sigma_z/c$ )	> 100 fsec
$\Delta E/E$	
$CO_2$ laser	
$\lambda_0$	10.3 $\mu\text{m}$
$w_0$ ( $1/e^2$ radius)	30 - 100 $\mu\text{m}$
$Z_R$	0.3 - 3 mm
Pulse energy	50 J
Pulse length	500 fsec
Pulse power	100 TW
Polarization	Linear

# PICU concept - PIC simulation

$n_0 = 2 \times 10^{17} \text{ cm}^{-3} \rightarrow$  artificial thin - wide beam

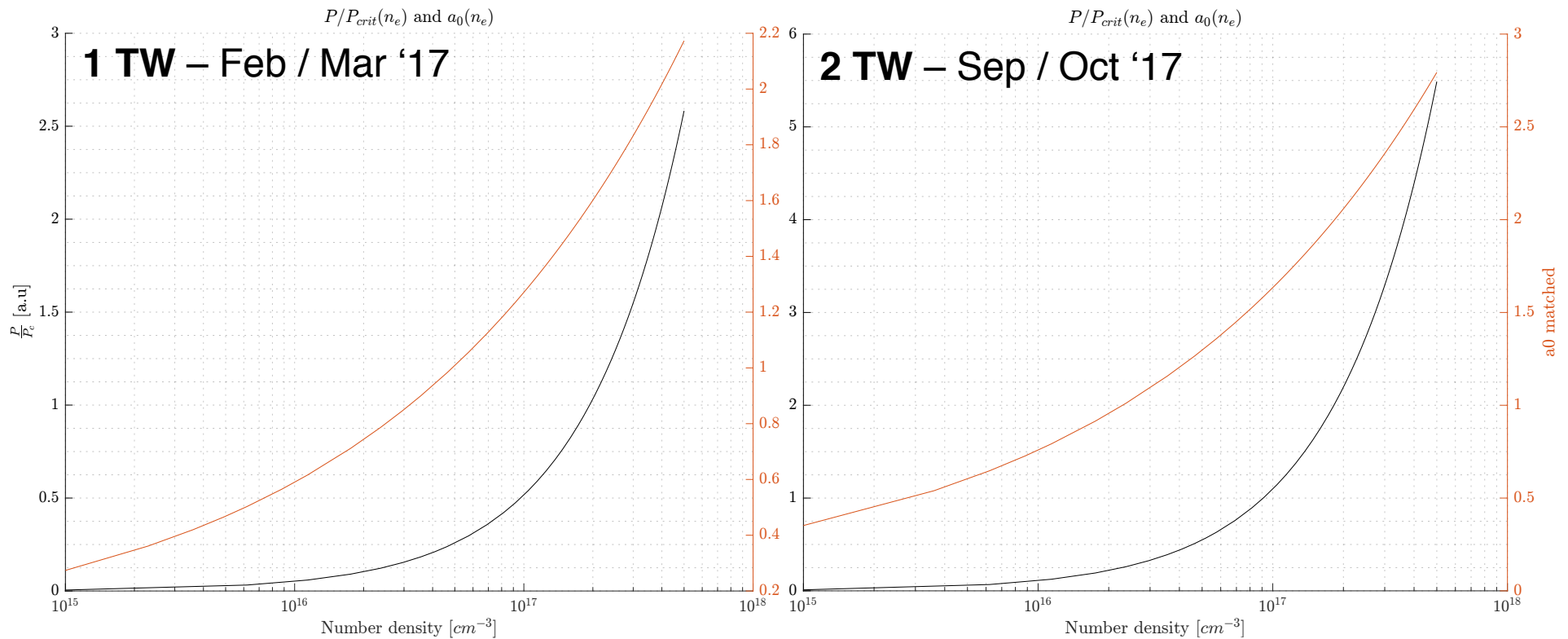


$\sim 40 \text{ GV / m}$  – Transverse focusing fields [ $\sim 100 \sqrt{(n_0/10^{18} \text{ cm}^{-3})} \text{ GV/m}$ ]

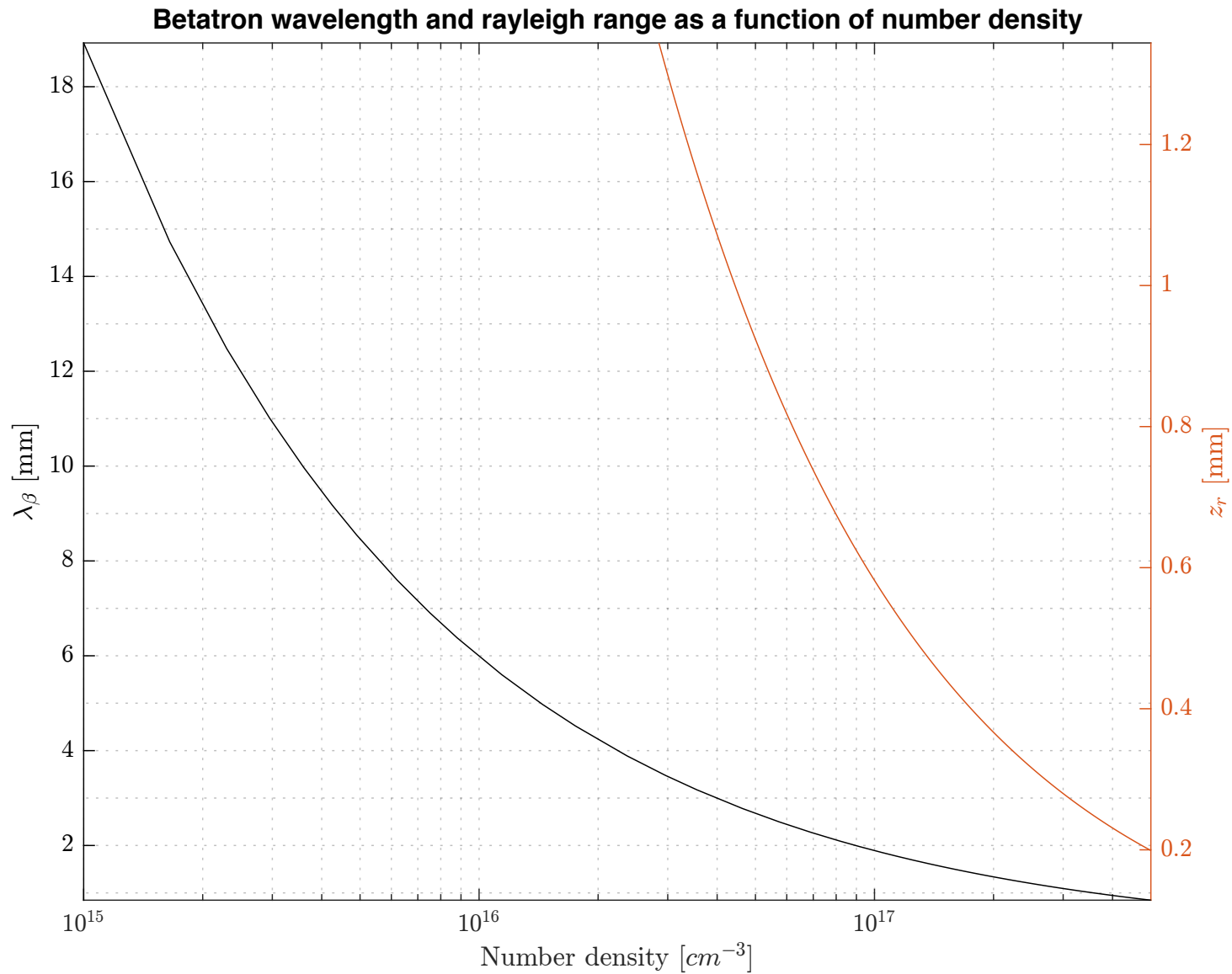
Effective Undulator Magnetic field  $\rightarrow B_U \sim E_{\text{plasma}} / c = \mathbf{100 \text{ T}}$

Undulator wavelength  $\rightarrow \lambda_u \sim \mathbf{1.5 \text{ mm}}$

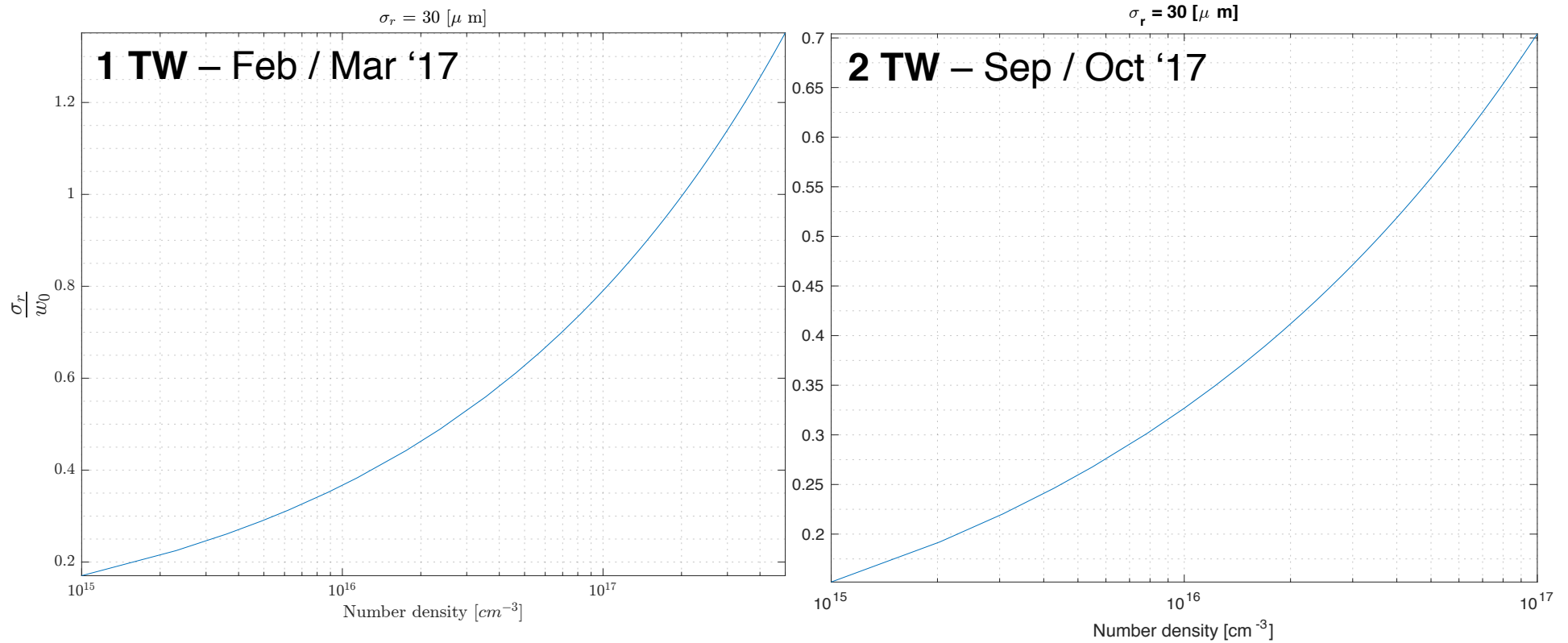
# Laser self-guiding vs. $a_0$ parameters



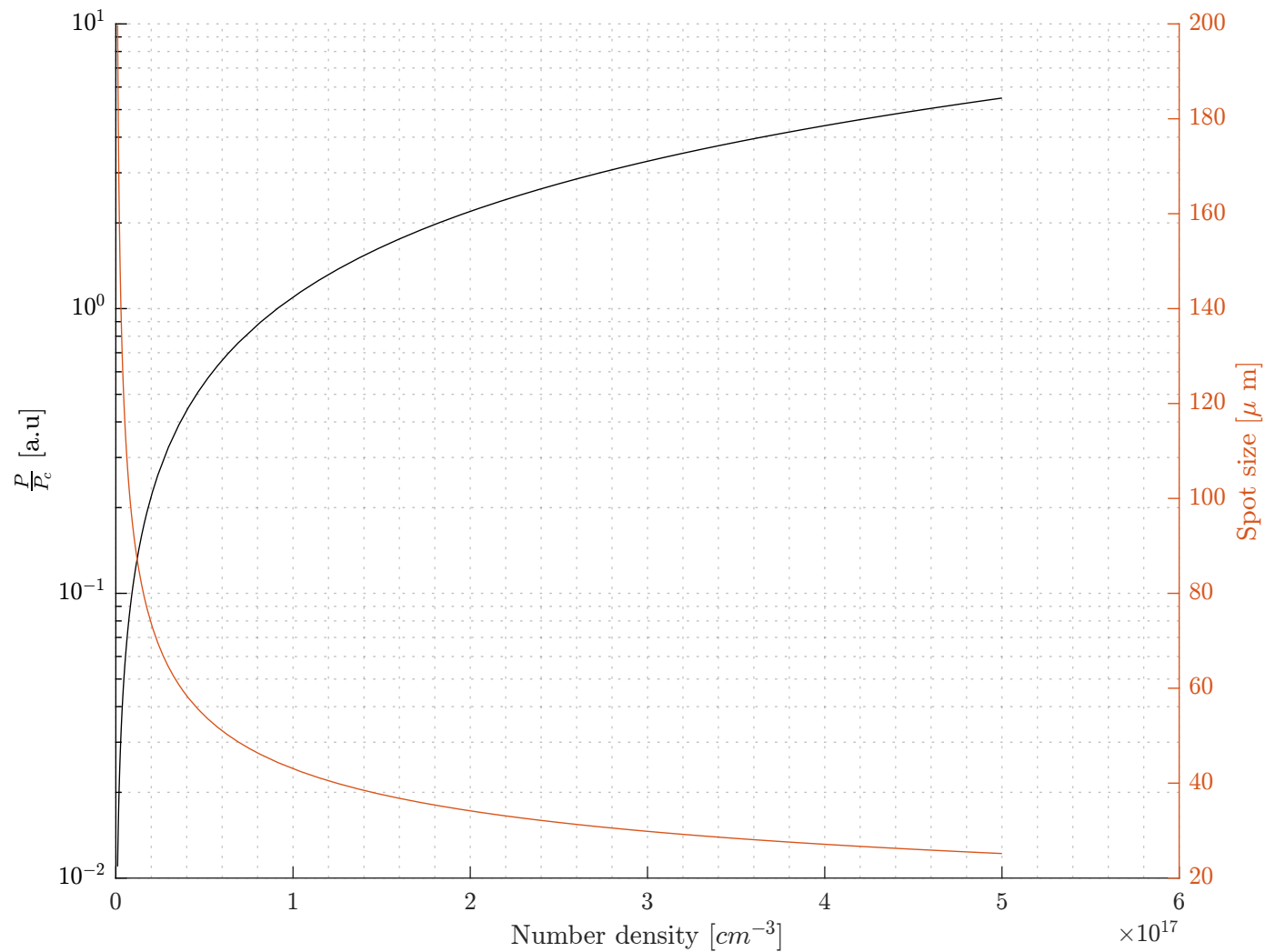
# Betatron wavelength vs laser-guiding length



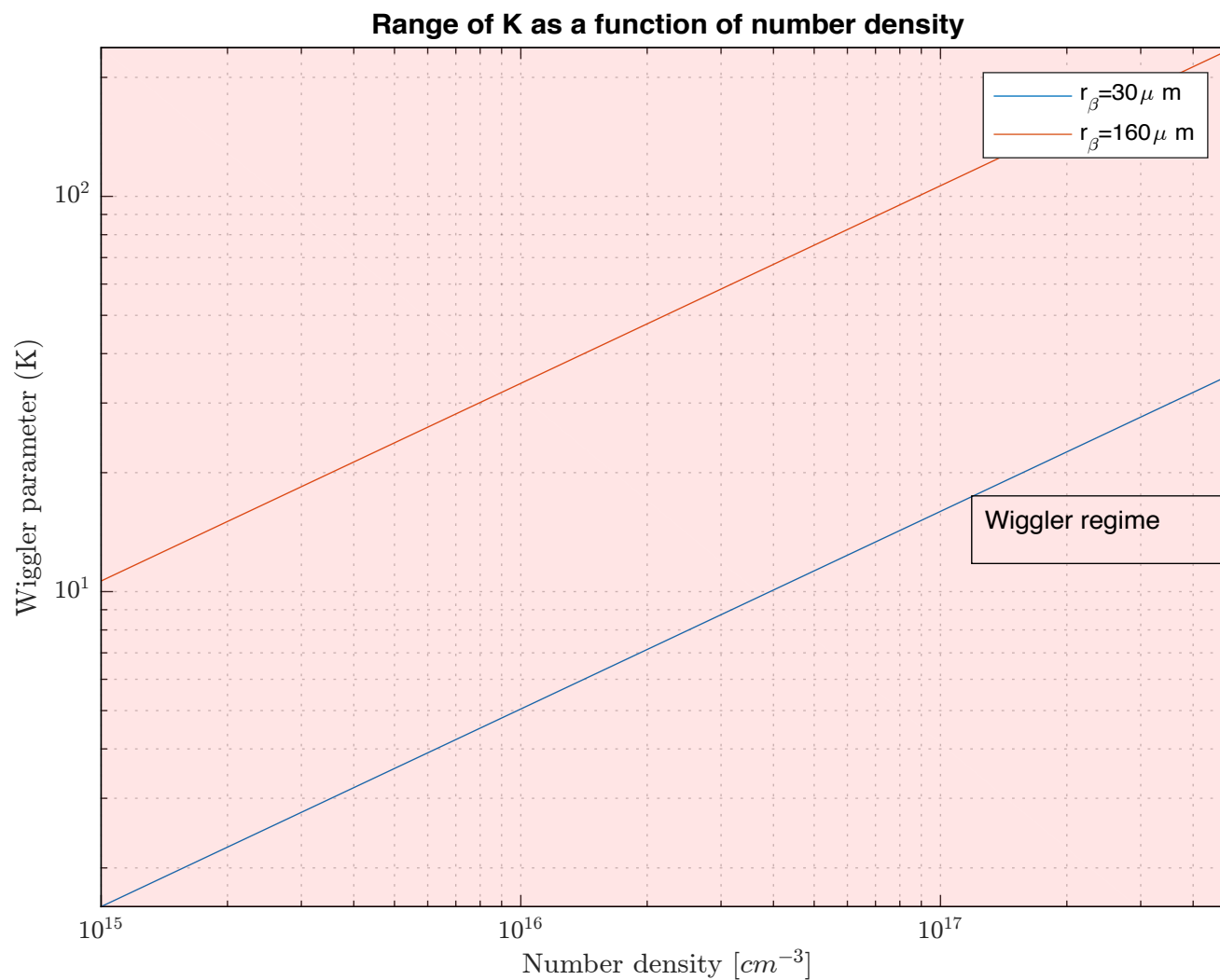
# e-beam size vs laser focal-spot size



# Ion-channel trans. size – laser guiding / cavitation

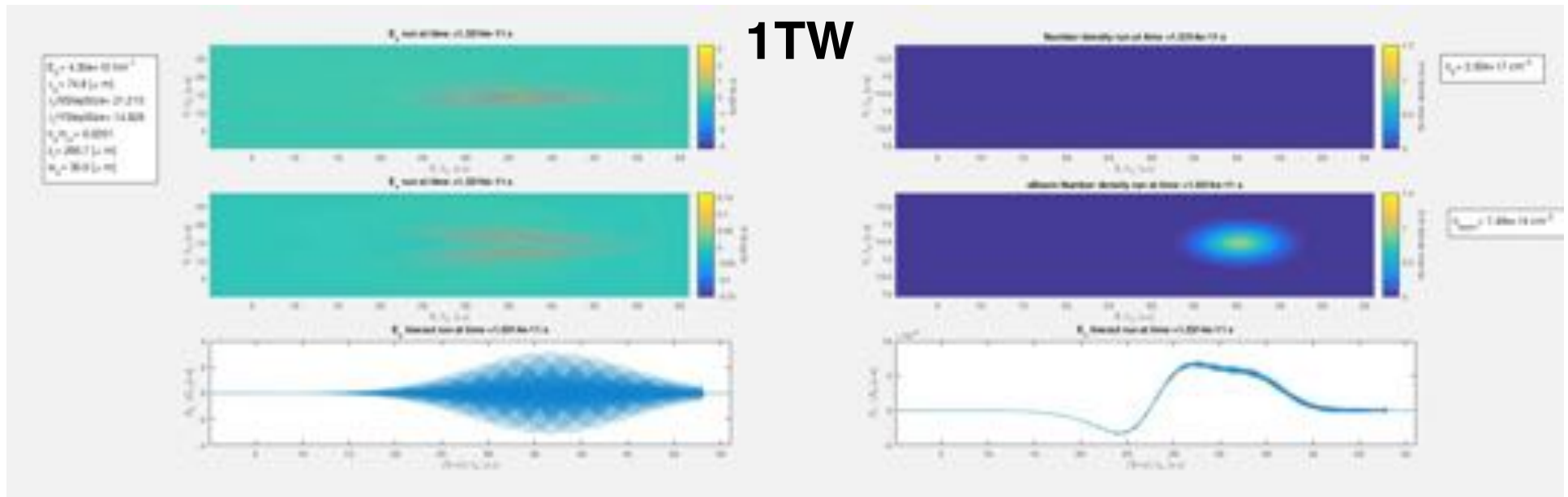


# Tuning $K_{ICU}$ in PICU

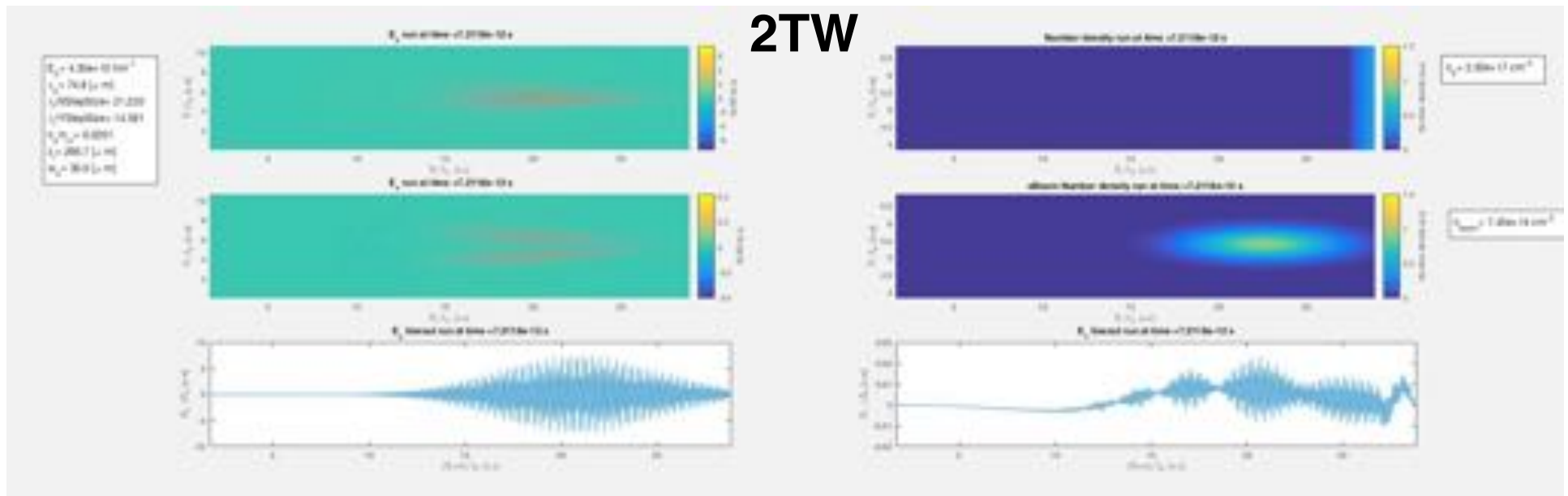


# $2 \times 10^{17} \text{ cm}^{-3}$ - PIC simulations

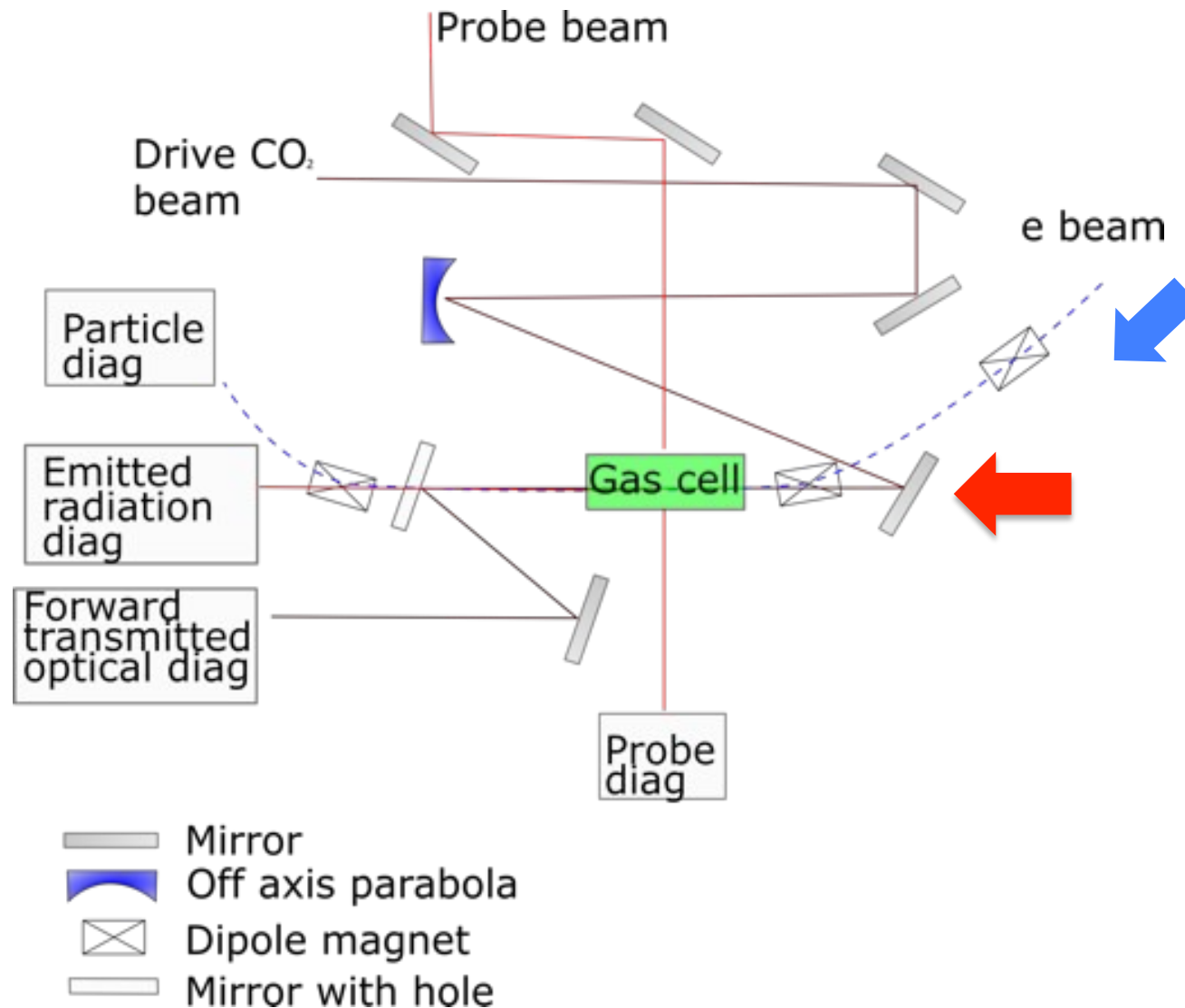
1TW



2TW



# Proposed Expt. Setup



# $2 \times 10^{17} \text{ cm}^{-3}$ – expected results

Table 3: Ion-Channel Undulator / Plasma Undulator properties at  $2 \times 10^{17} \text{ cm}^{-3}$

Plasma parameters	1TW	2TW
Density	$2 \times 10^{17} \text{ cm}^{-3}$	
Critical Power ( $P_c$ )	1.1 TW	1.1 TW
$P/P_c$	0.88	1.87
matched- $w_0$	32 $\mu\text{m}$	36 $\mu\text{m}$
$a_0$	1.52	1.95
$\lambda_\beta$	1.45 mm	1.45 mm
$Z_R$ (matched- $w_0$ )	0.32 mm	0.4 mm
$\sigma_r/w_0$	0.9	0.8
$\gamma_\phi/\gamma_{beam}$	0.05	0.05
$K_{ICU}$ (undulator strength)	20.8	20.8
$\lambda_{ICU} (\lambda_\beta/2\gamma_{beam}^2)$	26 nm	26 nm
$P_{ICU}$ (rad. power)	0.045 W	0.045 W
$E_{ICU}$ (energy @ 1 $\lambda_\beta$ )	$200 \times 10^{-12} \text{ J}$	$200 \times 10^{-12} \text{ J}$
$N_{ph}$ (@ 1 $\lambda_\beta$ )	$2.7 \times 10^{10}$	$2.7 \times 10^{10}$

# $5 \times 10^{16} \text{ cm}^{-3}$ – expected results

Table 4: Ion-Channel Undulator / Plasma Undulator properties at  $5 \times 10^{16} \text{ cm}^{-3}$

Plasma parameters	1TW	2TW
Density	$5 \times 10^{16} \text{ cm}^{-3}$	
Critical Power ( $P_c$ )	3.9 TW	3.9 TW
$P/P_c$	0.26	0.5
matched- $w_0$	48 $\mu\text{m}$	54 $\mu\text{m}$
$a_0$	0.1	1.3
$\lambda_\beta$	2.7 mm	2.7 mm
$Z_R$ (matched- $w_0$ )	0.72 mm	0.9 mm
$\sigma_r/w_0$	0.6	0.6
$\gamma_\phi/\gamma_{beam}$	0.1	0.1
$K_{ICU}$ (undulator strength)	11	11
$\lambda_{ICU}$ ( $\lambda_\beta/2\gamma_{beam}^2$ )	52 nm	52 nm
$P_{ICU}$ (power)	$5 \times 10^{-3} \text{ W}$	$5 \times 10^{-3} \text{ W}$
$E_{ICU}$ (energy @ 1 $\lambda_\beta$ )	$50 \times 10^{-12} \text{ J}$	$50 \times 10^{-12} \text{ J}$
$N_{ph}$ (@ 1 $\lambda_\beta$ )	$1 \times 10^{10}$	$1 \times 10^{10}$

# $5 \times 10^{15} \text{ cm}^{-3}$ – expected results

Table 5: Ion-Channel Undulator / Plasma Undulator properties at  $5 \times 10^{15} \text{ cm}^{-3}$

Plasma parameters	1TW	2TW
Density	$5 \times 10^{15} \text{ cm}^{-3}$	
Critical Power ( $P_c$ )	38.7 TW	38.7 TW
$P/P_c$	0.03	0.05
matched- $w_0$	103 $\mu\text{m}$	117 $\mu\text{m}$
$a_0$	0.5	8.5 mm
$\lambda_\beta$	8.46 mm	13.4 mm
$Z_R$ (matched- $w_0$ )	3.34 mm	4.3 mm
$\sigma_r/w_0$	0.29	0.26
$\gamma_\phi/\gamma_{beam}$	0.3	0.3
$K_{ICU}$ (undulator strength)	3.6	3.6
$\lambda_{ICU} (\lambda_\beta/2\gamma_{beam}^2)$	170 nm	170 nm
$P_{ICU}$ (rad. power)	0.0002 W	0.0002 W
$E_{ICU}$ (energy @ 1 $\lambda_\beta$ )	$5 \times 10^{-12} \text{ J}$	$5 \times 10^{-12} \text{ J}$
$N_{ph}$ (@ 1 $\lambda_\beta$ )	$4 \times 10^9$	$4 \times 10^9$

## Summary and Key-points

- $\tau_{laser} \gg \lambda_{pe}$  – **GOOD** for **LONG & UNIFORM** Ion-Channel
- Trans. & Long. size of the Ion-Channel – **GOOD** for **e-beam overlap**  
**10 $\mu$ m laser excites plasma structures ~ much larger than 1 $\mu$ m laser**
- PIC simulations – significant undulation of beam e<sup>-</sup> trajectories in the channel
- X-ray pulses – tunable wavelength from **10nm** to **200nm** – via plasma-density
- X-ray pulses – **10<sup>8</sup>** to **10<sup>10</sup>** photons
- Tuning **K<sub>ICU</sub>** – from **5** to **100**
- Planned applications – medical imaging with **advanced imaging** techniques

## Imperial-Gemini 1um laser - Medical Imaging results



courtesy : Dr. Jason Cole, Imperial College

## Time Request

2 slots of 3 weeks in 2017

**1TW** (@3.5ps) [Early '17] & **2TW** (@1.7ps) [Late '17]

1 week setup time  
2 week runs

**Thank You !**

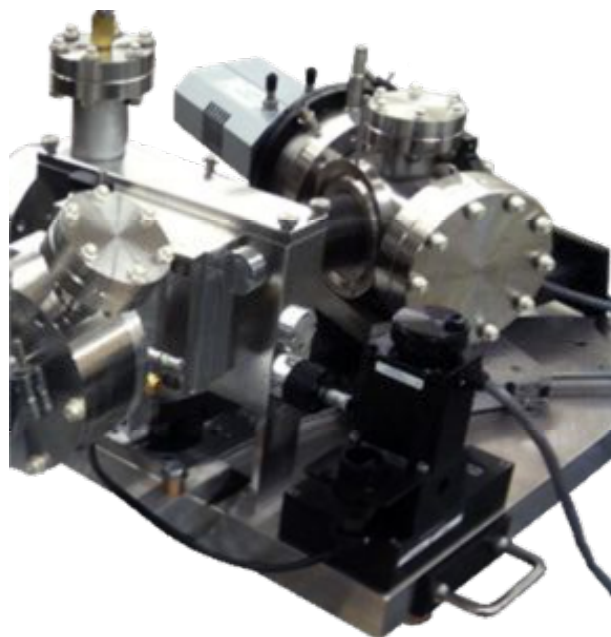
## Backup slides

# UV spectrometer

## 1m f.l. Soft X-ray and Extreme UV Monochromator

The 248/310 is a 1000 mm focal length Rowland circle grazing incidence vacuum monochromator. It has 0.02 nm fwhm spectral resolution with 1200 g/mm grating. Its precision slits are micrometer adjustable from 0.005 to 0.5 mm. The 248/310 features a chord-length meter and manually operable wavelength drive for years of accurate and reproducible wavelength positioning. The scan controller provides computer/software control. The high performance instrument provides excellent performance from 1 nanometer up to 300 nm in the UV.

Use the 248/310 for XUV, SXR or extreme UV applications. The compact housing is easily adapted to most experiments. We can provide it complete with vacuum pumps, microchannel plates and CCD detectors.



**1 to 310nm range | Direct-CCD, scanning slit, MCP configurations | Large assortment of gratings**